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► **To cite this version:**

Mohamed Amine Hebri, Abderrahmane Rebhaoui, Grégory Bauw, Jean-Philippe Lecointe, Stéphane Duchesne, et al.. Power density improvement of axial flux permanent magnet synchronous motor by using different magnetic materials. XXVII Symposium Electromagnetic Phenomena in Nonlinear Circuits (EPNC), Jun 2022, Hamburg, Germany. <hal-04290917>

HAL Id: hal-04290917

<https://univ-artois.hal.science/hal-04290917v1>

Submitted on 10 Jan 2024

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POWER DENSITY IMPROVEMENT OF AXIAL FLUX PERMANENT MAGNET SYNCHRONOUS MOTOR BY USING DIFFERENT MAGNETIC MATERIALS

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Abstract - This paper presents a study to improve the power density and efficiency of permanent magnet synchronous machines for electric traction applications with high operating speed. The studied axial flux permanent magnet motor is equipped of a yokeless dual-rotor. Several comparative studies have shown that this topology has the best power density and efficiency and that it allows a good cooling. This work is based on the use of different magnetic materials for an optimal design of the stator and rotor magnetic circuits to improve the motor performance. The candidate magnetic materials, perfectly adapted to the constraints of eMobility, are 3% Si-Fe Non-Oriented grain Electrical Steel (NOES), 3% Si-Fe Grain-Oriented Electrical Steel (GOES) and Iron-Cobalt Permendur electrical steel (Co-Fe). The main objective is to exploit, as far as possible, the optimal performances of each magnetic material in terms of high saturation flux density in order to reduce the geometrical dimensions of the stator teeth and rotor yoke and, consequently, to gain in overall motor mass. In addition, the benefit bring by the low specific losses is evaluated by calculating the overall efficiency of the machine.

I. INTRODUCTION

The road transport sector is a major source of greenhouse gas emissions, including CO₂. For this reason, new restrictions and limitations of the CO₂ emissions are implemented by the European Union in order to reach carbon neutrality in 2050 [1]. For example, in Europe and in 2020, CO₂ emissions are limited to 95g/km on average for new cars [1]. This context leads car manufacturers to reduce their environmental impact in order to avoid penalties when the emissions exceed defined thresholds. As a result, and for several years, these manufacturers have been offering in their ranges hybrid cars (HEV), plug-in hybrids (PHEV), and fully battery electric cars (BEV). To make these cars economic and efficient and to improve the BEV autonomy, the manufacturers have the objective to improve the efficiency of the whole electric powertrain [1-2].

Improving efficiency requires to reduce losses in each element of the powertrain, as well as reducing its energy consumption due to the total weight of the components. This paper focuses on the electric motor by improving its efficiency and power to weight ratio. In automotive traction applications, the radial flux Permanent Magnet Synchronous Motors (PMSMs) are generally used due to its high-power density, high efficiency, compact size, and manufacturing simplicity [2-3]. Axial flux PMSMs are good candidate as their power density may be even higher. To further improve the power density of axial-flux PMSM, there are several ways:

- the current density can be increased, but is limited by the thermal constraints and the cooling system [4];
- the maximum rotation speed can be increased, but is limited by mechanical constraints: the peripheral speed and the transmission system [5];
- the use of permanent magnets with very high energy density are recommended (NdFeB, SmCo) [6] but their environmental footprint are non-negligible;
- the use of magnetic materials with high permeability, high saturation flux density and low specific losses is also a way to analyse, as Grain-Oriented Electrical Steel (GOES), or Iron-Cobalt Permendur electrical steel (CoFe) [7-9].

In this paper, the authors analyze the impact of using different electrical steels in the magnetic circuit of a yokeless dual-rotor axial flux PMSM. Conventionally, electric motors for automotive applications are designed with Non-Oriented grain Electrical Steel (NOES), which are well suited for rotating field applications [5]. In this work, other magnetic materials is used as GOES. The latter is commonly applied in power transformer magnetic circuits [5, 10]; it is characterized by a very high magnetic permeability, a high saturation flux density and low specific losses, compared to the conventional NOES. Similarly, Permendur CoFe, which is commonly used in aeronautical applications, is an attractive candidate due to its very high saturation flux density compared to NOES and GOES [9]. The high level of saturation allows to reduce the size of the stator teeth and rotor yoke and, thus, to increase the power density at iso-torque. The low specific losses increase the efficiency of the machine [10].

The paper is separated in four sections. First, a comparison between different candidate magnetic materials for e-mobility is presented, in terms of B-H curves (permeability and flux density level at saturation) and specific losses. Second, the studied motor is presented in its complete form and its equivalent 2-D Finite Element model, as well as the main parameters. In addition, the design approach and the integration of materials are explained. A brief presentation of the software and the simulation parameters is made. Third, the FEA numerical calculations results are presented in the form of mono-objective and multi objective optimization. The performance in the torque-speed plane is calculated for a selected structure. Four, the main results are presented and discussed in the conclusion.

II. MAGNETIC MATERIALS

Fig. 1-a shows the B-H curves for the three magnetic materials analyzed in this paper: NOES, GOES and the Permendur Hiperco50, which thicknesses are 0.20mm, 0.20mm and 0.15mm respectively. The measurements are obtained with a standardised Single Sheet Tester (SST) frame at 50 Hz.

The curves show that the GOES strips magnetized along the Rolling Direction (RD) have a high maximal permeability, about 31000, over 2 times more compared to NOES and Permendur (Fig. 1-b). On the other hand, GOES is highly anisotropic, which means that the performances in the Transverse Direction (TD) are much less interesting. The Permendur Hiperco50 sheet has a high saturation flux density value, over 2.25T, versus 1.83T for the conventionnel NOES and 2.03T for the GOES magnetized along the RD (Table I).

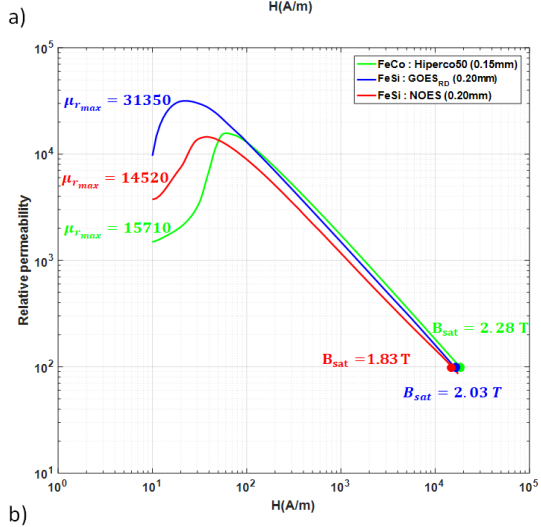
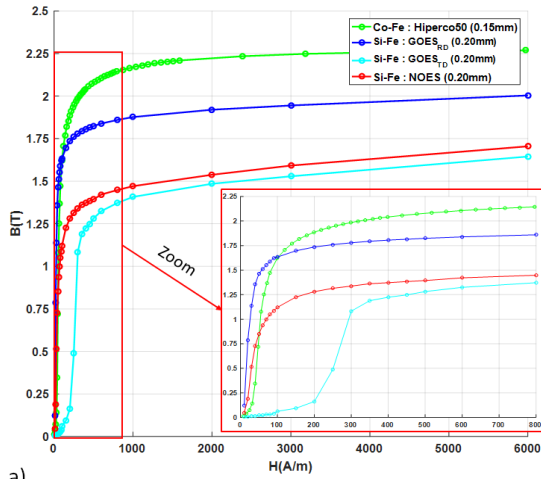


Fig.1. Performance of the different magnetic sheets used at 50Hz: a) B-H curves, b) relative permeability

TABLE I
MAGNETIC PROPERTIES

	Saturation flux density @ $\mu_r=100$	Maximal relative permeability	Mass density
3% Si-Fe - NOES	1.83 T	14520	7650 kg/m ³
3% Si-Fe - GOES	2.03 T	31350	7650 kg/m ³
Co-Fe : Hiperco50	2.28 T	15350	8120 kg/m ³

Fig. 2 shows the specific losses for the different magnetic sheets when frequency is 500Hz. The GOES sheet magnetized along the RD presents the lowest iron losses, compared to the conventional NOES sheet, at iso-thickness.

In parallel, GOES strips of 0.20mm thickness have iron losses almost equal to the Co-Fe losses strips of 0.15mm thickness, at 500Hz and for flux density values lower than 1.8T. On the other hand, the performances of the GOES sheet following the TD are not interesting anymore.

The Permendur Hiperco50 steel becomes advantageous for the high frequency operating ranges because of its low thickness which limits the eddy current losses in the laminations.

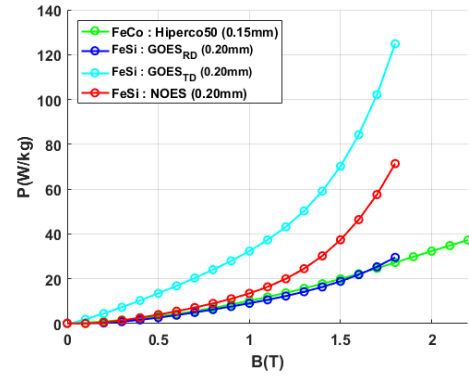


Fig.2. Specific losses for the different magnetic sheets used at 500Hz

III. DESIGN APPROACH

The studied axial flux dual-rotor and yokeless PMSM is shown in Fig. 3-a. In order to simplify the study and the modelling, the authors has modelled a 2D structure at the average radius (Fig. 3-b) of the axial flux PMSM. The main motor parameters are presented in Table II.

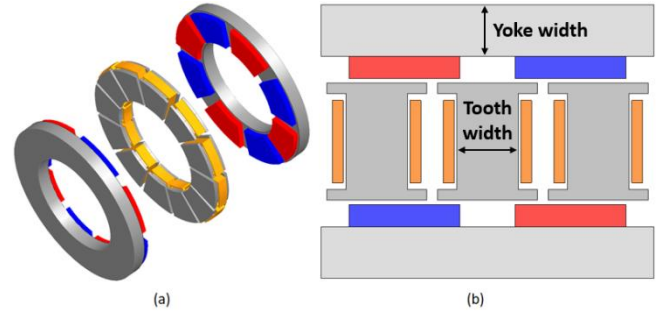


Fig.3. The PMSM structure studied: a) in 3D, b) in 2D at average radius

TABLE II
MOTOR PARAMETERS

Slot / Pole number	12 / 8
Inner / Outer radius	60mm / 100mm
Base rotational speed	10000rpm
Number of series turns per phase	60
Rated current	130Arms
Airgap	1.3mm
Magnet width	6.5mm

To improve power density and efficiency of the active parts of the studied axial flux, the authors propose to analyse the impact of using non-conventional materials for the magnetic stator and rotor circuits.

The strategy relies on the intrinsic properties of these materials but also on the topology of the magnetic circuit:

- It can be taken advantage of the Hiperco50 low thickness of 0.15mm to reduce the iron losses (eddy current losses) and consequently to improve the efficiency. Its high saturation flux density allows to reduce the size of the circuits.
- GOES has good performance in the RD, which is usable in the stator teeth where the field lines are quasi-unidirectional along the axial direction as shown in fig. 4.
- In the rotor yoke, despite the rotating direction of the field (Fig. 4), possibility of using GOES can be studied.

The geometric parameters which are optimized are the rotor yoke width and the tooth width, respecting the necessary slot area for the wire arrangement, as well as the saturation levels of the sheets. The aim is to find the optimal geometrical dimensions for a high-power density, in the power range between 90kW and 105kW, at a given rotational speed of 10000rpm and at a given current density (15Arms/mm²).

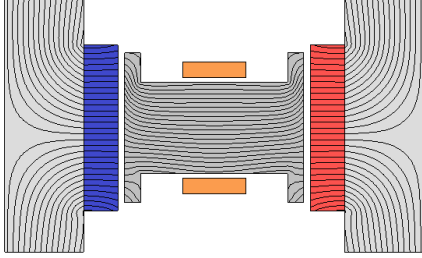


Fig.4. Flux lines in a pole of axial flux PMSM

The 3 magnetic materials described above NOES, GOES, and Hiperco50 (Fig.1) are combined in the stator teeth and the rotor yoke, which lead to 9 configurations of magnetic circuits described in Table III.

TABLE III
COMBINATIONS FOR THE MAGNETIC CIRCUIT

Structures	Tooth material	Yoke material
Tn-Yn	NOES	NOES
Tn-Yg	NOES	GOES
Tn-Yh	NOES	Hiperco50
Tg-Yn	GOES	NOES
Tg-Yg	GOES	GOES
Tg-Yh	GOES	Hiperco50
Th-Yn	Hiperco50	NOES
Th-Yg	Hiperco50	GOES
Th-Yh	Hiperco50	Hiperco50

IV. FEA-2D MODELING

The study is based on a Finite Element Analysis (FEA) using the commercial JMAG software. This software application allows to take into account both magnetic circuit saturation and magnetic anisotropy when GOES is modelled. The anisotropy is modelled with a diagonal permeability tensor based on measurements of the magnetic characteristics in RD and TD.

$$B = \begin{bmatrix} \mu_x & 0 \\ 0 & \mu_y \end{bmatrix} \times H \quad (1)$$

The calculation of iron losses is performed using the classical approximation of the Steinmetz model (taking into account the harmonics) which is based on standardized measurements. For GOES, the same model is used with bidirectional coefficients:

$$P_{core_loss} = \sum_{i=1}^N \left\{ \begin{aligned} &(K_{hRD} \cdot B_{RD}^\alpha + K_{hTD} \cdot B_{TD}^\alpha) \cdot f^\beta \\ &+ \\ &(K_{eRD} \cdot B_{RD}^\gamma + K_{eTD} \cdot B_{TD}^\gamma) \cdot f^\delta \end{aligned} \right. \quad (2)$$

where i is the harmonic rank, N is the highest harmonic, f is the operating frequency, B_{RD} , B_{TD} are the maximum level of flux densities according to the RD and TD. The coefficients K_h , K_e , α , β , γ , and δ are determined with the measurement data.

The boundary conditions (i.e., periodicity and symmetry conditions) allow the machine geometry to be reduced to 3 slots/2 poles and to one rotor and a half stator (Fig. 5). This reduces the computational time. The mesh of 9304 elements is shown in Fig. 5; where the airgap is structured with 3 radial divisions of 0.43mm mesh size.

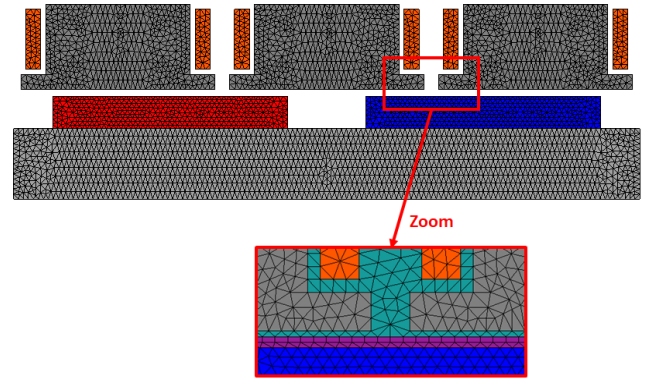


Fig.5 Mesh of the studied structure

V. FEA-2D RESULTS

a) Parameter variations and reference results

In this part, the numerical results of the new structures presented in table III are shown. A comparison of the power densities and efficiencies between the different structures according to the different magnetic materials and the geometrical dimensions of the stator teeth and the rotor yoke is shown in Fig. 6 and 7. The range of variation of the yoke thickness and the tooth width are respectively from 9 to 11mm and from 19 to 29mm. These limits varied depending on the structure, in order to satisfy the saturation flux density constraint in the magnetic circuits and the power range between 90 and 105kw.

The power density calculation only considers the active parts in the weight calculation. The calculation of the efficiency takes into account the iron losses, magnet losses and Joule losses considering the end coils and the skin effect/proximity effect.

For the full NOES conventional reference structure (Tn-Yn), the maximum power density is 9.39kW/kg obtained with a 24mm tooth width and a 12mm yoke width (Fig. 6-a). For the same structure, the maximum efficiency is 98.14%, obtained with a tooth width of 29mm and a rotor yoke width of 16mm (Fig. 7-a).

b) Power density optimization:

The Table IV and Fig. 6 allows to draw the following conclusions about the power density modifications :

- Keeping the NOES sheet in the rotor yoke, the stator teeth is replaced with non-conventional magnetic materials:
 - The use of GOES and Hiperco50 sheets in the stator teeth allows to improve the power density. GOES (Tg-Yn) leads to obtain a maximum power density of 9.57kW/kg, 2% more compared to the reference structure and with a yoke width of 12mm and 22mm tooth width (Fig. 6-d);
 - The use of the Hiperco50 sheet (Th-Yn) increases the power by 1.9% (9.56kW/kg) with a yoke thickness of 11mm and a tooth width of 19mm (fig. 6-g).
- Keeping the NOES in the stator teeth and replacing the rotor yoke with GOES and Hiperco50 also allow to improve the power density:
 - By using the GOES (Tn-Yg), the maximum power density is 9.74kW/kg, i.e. an increase of 3.7%, with a yoke width of 11mm and a tooth width of 24mm (Fig. 6-b);
 - Hiperco50 (Tn-Yh) leads to a maximum power density of 9.91kW/kg, with yoke width of 11mm and a tooth width of 19mm (fig. 6-g).
- When non-conventional materials is in both stator and rotor magnetic circuits:
 - the Full GOES structure allows to have a maximum power density of 9.94kW/kg for a yoke width of 11mm and a tooth width of 22mm;
 - A full Hiperco50 structure can give a max power density of 10.09kW/kg for a yoke width of 10mm and a tooth width of 20mm.
- For non-conventional mixed structures:
 - GOES teeth and a Hiperco50 yoke lead to a power density of 10.11kW/kg for a yoke width of 10mm and a tooth width of 22mm
 - Hiperco50 teeth and a GOES yoke provide 9.92kW/kg for a yoke width of 11mm and a tooth width of 20mm.

TABLE IV
MAXIMAL POWER DENSITIES AND GAIN

Structures	Max power density (kW/kg)	Gain (%)
Tn-Yn	9.39	-
Tn-Yg	9.74	3.72
Tn-Yh	9.91	5.53
Tg-Yn	9.57	1.91
Tg-Yg	9.94	5.85
Tg-Yh	10.11	7.66
Th-Yn	9.56	1.81
Th-Yg	9.92	5.64
Th-Yh	10.09	7.45

The use of Hiperco50 sheets in the rotor yoke is more advantageous than NOES and GOES sheets. The best structures in terms of power density improvement are the

mixed structure with GOES teeth and Hiperco50 yoke and the full Hiperco50 structure.

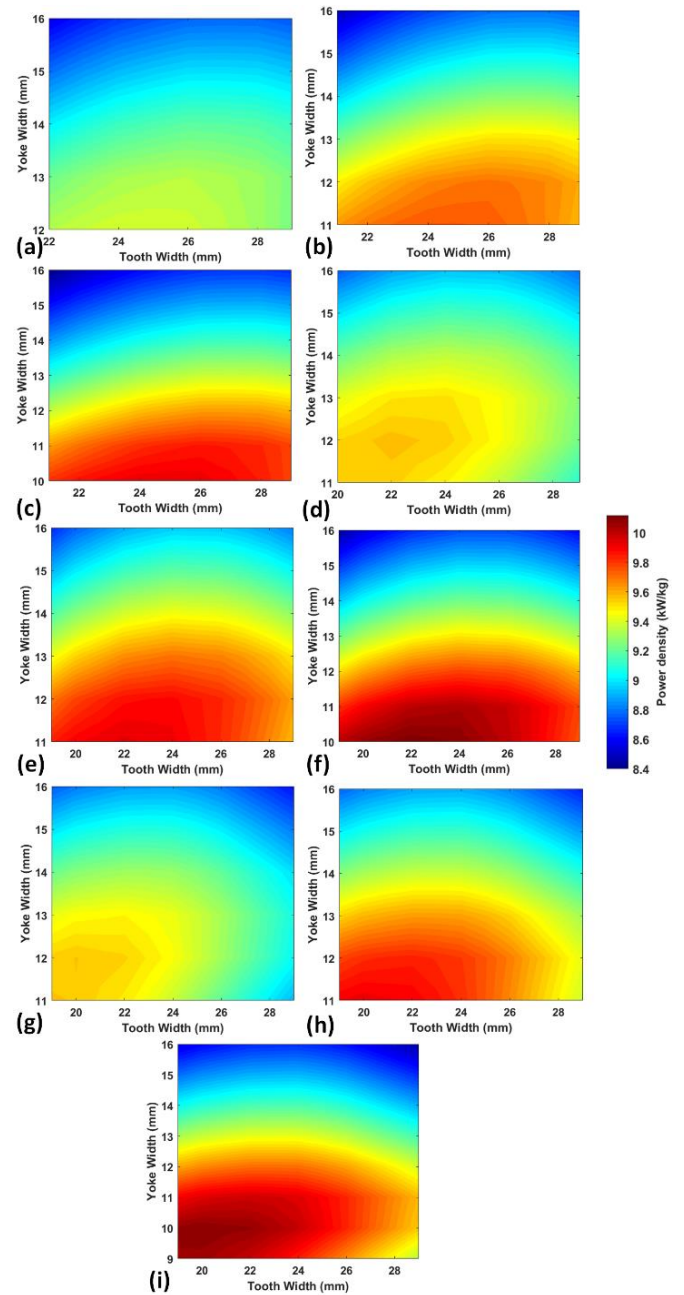


Fig.6. Variation of power density as a function of the tooth width and the yoke width for: a) Tn-Yn, b) Tn-Yg, c) Tn-Yh, d) Tg-Yn, e) Tg-Yg, f) Tg-Yh, g) Th-Yn, h) Th-Yg, i) Th-Yh

c) Efficiency optimization:

The use of different non-conventional materials in the magnetic circuit (stator and rotor) can also improve the efficiency of the electric motor. To do that, a mono-objective optimization for different structures as a function of geometrical dimensions (tooth width, yoke width) is performed. Results are given in Fig. 7 and the maximum efficiencies obtained for each motor are given in Table V. The following conclusions can be written:

- The GOES in the rotor yoke is not advantageous, because the losses in the rotor increase; so this configuration is not adapted to this structure.
- On the other hand, using GOES in the stator leads to a strong improvement of the maximum efficiency with a benefit of more than 0.06%, compared to the NOES structure.
- Hiperco50 in the teeth allows to obtain a better improvement of the efficiency. The best structures in term of efficiency improvement are:
 - the mixt Hiperco50 tooth – NOES yoke structure (Th-Yn), with 25mm tooth width and 16mm yoke width, with an improvement of 0.10% compared to the NOES reference structure;
 - the full Hiperco50 structure (Th-Yh), with 24mm tooth width and 15mm yoke width, with a 0.11% improvement.

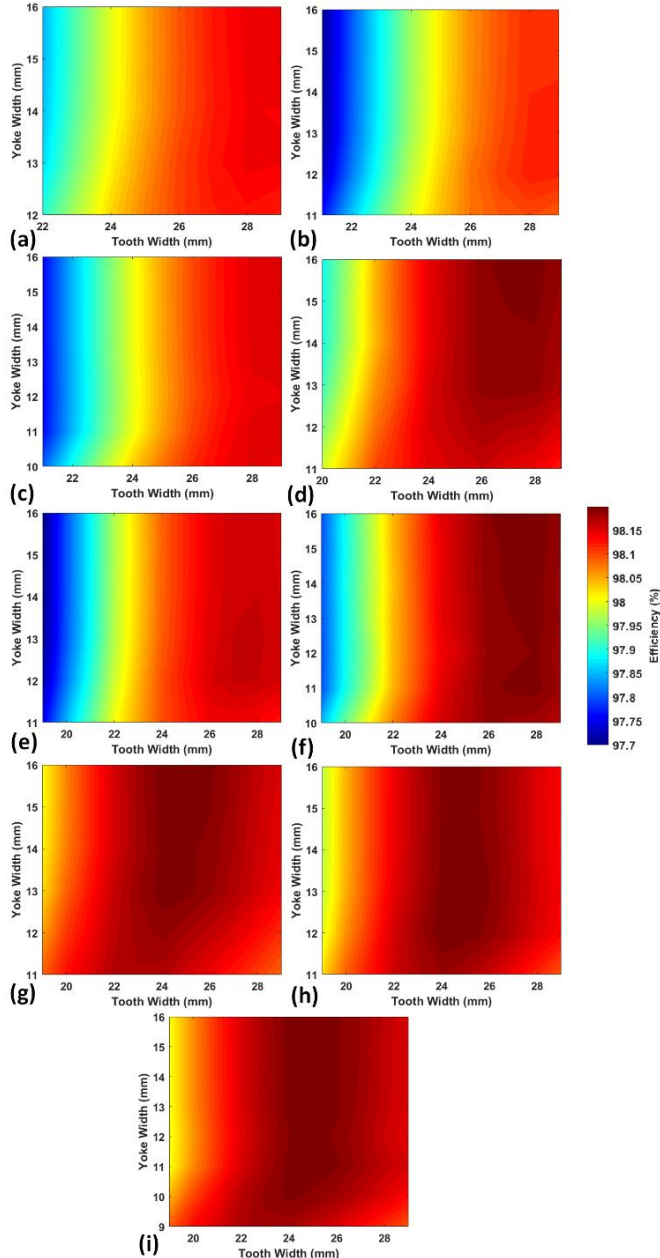


Fig.7. Variation of the efficiency as a function of the tooth-width and the yoke-width for: a) Tn-Yn, b) Tn-Yg, c) Tn-Yh, d) Tg-Yn, e) Tg-Yg, f) Tg-Yh, g) Th-Yn, h) Th-Yg, i) Th-Yh

TABLE V
MAXIMAL EFFICIENCY AND IMPROVEMENT

Structures	Max efficiency (%)	Improvement (%)
Tn-Yn	98.14	-
Tn-Yg	98.11	-0.03
Tn-Yh	98.15	0.01
Tg-Yn	98.20	0.06
Tg-Yg	98.16	0.02
Tg-Yh	98.21	0.07
Th-Yn	98.24	0.10
Th-Yg	98.15	0.01
Th-Yh	98.25	0.11

d) Multi-objective optimization:

For a better design, a multi-objective optimization has been made in order to design the optimal structure in terms of efficiency and power density improvement, depending on the different magnetic materials and on the teeth and yoke geometric dimensions.

Fig. 8 shows the Pareto fronts for the 9 structures described in Table III. The use of non-conventional magnetic materials, with full or mixed structures, always allows to improve the performances of the electric motor in terms of power density and efficiency, except for the structure with NOES conventional teeth and GOES yoke (Tn-Yg) for which only the power density is improved. The top three improved structures in power density and/or efficiency are:

- the full Hiperco50 structure (Th-Yh);
- the mixed GOES teeth - Hiperco50 yoke structure (Tg-Yh);
- the mixed Hiperco50 teeth - NOES yoke structure (Th-Yn).

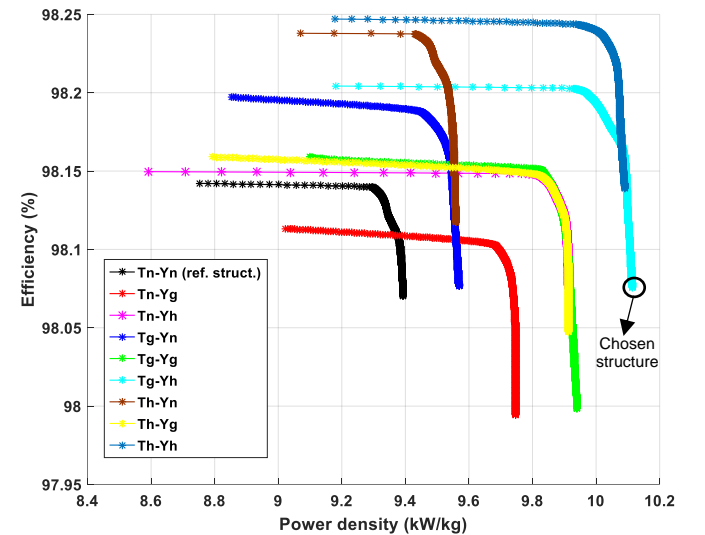


Fig.8. Variation of the optimization criteria (Pareto front)

e) Performance of the selected structure:

The mix GOES teeth - Hiperco50 yoke structure (Tg-Yh) is chosen for our motor, with a yoke width of 10mm and a tooth width of 22mm. It has been selected from the Pareto front (Fig. 8) and it provides the maximal power density of 10.1kW/kg and an efficiency of 98.08% at 10000rpm and a 130Arms current.

The efficiency of the chosen motor at different operating points in the torque-speed plane is shown in Fig. 9. It is plotted for both operating modes: constant torque and flux weakening, using the MTPA control strategy. The map is calculated by FEA considering the iron losses, eddy current losses in the magnets and Joule losses considering coil-ends and the skin effect/proximity effect [11]. The structure has a very high efficiency in the constant torque operating range (98.38%). It degrades with the flux weakening when the speed increases and at low load (89.57%). This is due to the increase in iron losses, losses in the permanent magnets and Joule effect losses at high frequency.

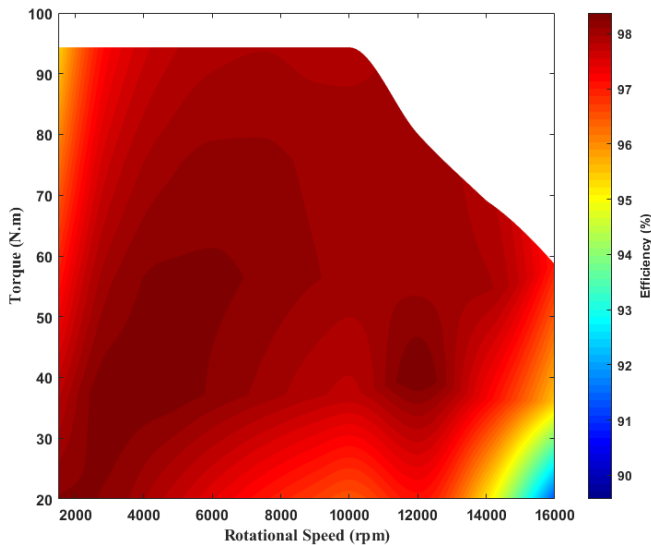


Fig.8. Efficiency maps of the selected motor.

V. CONCLUSION

In this paper, the effects of using different magnetic materials (NOES, GOES and Hiperco50) in the magnetic circuit (stator-rotor) of a 12-tooth-pole dual-rotor and yokeless PMSM axial flux machine, are numerical analysed in order to improve the power density and the efficiency. The study is based on FEA-2D numerical modelling of the machine at the average radius and at the rated operating point. The principle of the study is to integrate different materials in the magnetic circuit, which gives full or mixed structures in the rotor and the stator. Mono-objective/multi-objective optimizations are performed for an optimal design with the goal of improving power density and/or efficiency by varying the geometrical dimensions of the stator teeth and the rotor yoke.

GOES in the stator teeth and Hiperco50 in the stator teeth and/or in the rotor yoke can improve power density and efficiency simultaneously, compared to a conventional NOES structure. The best structures in terms of power density and/or efficiency are:

- the GOES teeth - Hiperco50 yoke structure for the best power density;
- the mixt of Hiperco50 teeth and NOES yoke for high efficiency;
- the full Hiperco50 structure to get high power density and the best performance.

The GOES teeth - Hiperco50 yoke structure, which has the highest power density (10.11kW/kg), has been chosen to evaluate its efficiency in the torque-speed plane. The maximum efficiency of this structure can reach a high value of 98.38% at low average speed-load. This efficiency decreases with increasing speed. These conclusions result from numerical calculations based on implemented models. The latter may suffer from intrinsic errors, as the loss model or the anisotropic model for GOES.

For future work, a FEA-3D optimization including thermal and mechanical simulations will be carried out in order to quantify the gain. The experimental tests, on a prototype motor, will also be performed.

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